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RADIO AND INFRARED OBSERVATIONS OF (ALMOST) ONE HUNDRED NON-SEYFERT MARKARIAN GALAXIES

Linda L. Dressel
Department of Space Physics and Astronomy, Rice University
Houston, TX 77251

ABSTRACT. I have measured the 13 cm flux densities of 96 non-Seyfert Markarian galaxies at Arecibo Observatory. Far infrared flux densities have been published for 78 of these galaxies in the IRAS catalog. I have compared the radio, infrared, and optical fluxes of these galaxies and of a magnitude-limited sample of "normal" galaxies to clarify the nature of the radio emission in Markarian galaxies. I find that Markarian galaxies of a given apparent magnitude and Hubble type generally have radio fluxes several times higher than the fluxes typical of "normal" galaxies of the same magnitude and type. Remarkably, the ratio of radio flux to far infrared flux (i.e., the synchrotron power per stellar ultraviolet thermal power) is nearly the same for most of these "star-burst" galaxies <u>and</u> for normal spiral disks. However, the compact and peculiar Markarian galaxies consistently have about 60% more radio flux per unit infrared flux than the other Markarian galaxies and the normal spirals. It is not clear whether this difference reflects a difference in the evolution of the star-bursts in these galaxies or whether there is excess radio emission of non-stellar origin.

1. INTRODUCTION

Photometric and spectroscopic studies of Markarian galaxies (Markarian et al. 1979 and references therein) have shown that, while some of them harbor Seyfert nuclei or BL Lac objects, the vast majority are unusually blue because of recent massive "bursts" of star formation. Although these galaxies have been found in ultraviolet surveys, they are expected to emit more of their radiation in the infrared, since the star-forming regions show heavy extinction by dust. They should also be unusually bright radio sources for their Hubble type and optical luminosity, due to high supernova rates. The relationships between radio, infrared, and blue luminosity can be used to clarify how radio emission is produced in star-forming regions. Below, I describe radio and infrared data for a large sample of bright nearby non-Seyfert Markarian galaxies, and I use this data to interpret the nature of the radio emission.

2. OBSERVATIONS

I have measured the 13 cm flux densities of 96 non-Seyfert Markarian galaxies brighter than 14.5 pg mag at Arecibo Observatory. Thirty-eight of the galaxies have flux densities above the conservative detection limit of 15 mJy (3σ noise, 5σ confusion). The measured flux densities below 15 mJy are not very accurate individually, but they are still useful statistically. I have compared this Markarian galaxy sample with the complete sample of galaxies brighter than 14.5 pg mag observed with the same system at Arecibo (Dressel and Condon 1978).

I have obtained far infrared fluxes for 78 of the 96 Markarian galaxies from the IRAS point source catalog (Lonsdale et al. 1985). (Five of the galaxies were not observed by IRAS, 11 were observed but not detected, and 2 were obviously confused). I have compared the far infrared flux from 43 to 123 microns ("FIR" in the catalog) to the 13 cm flux density for these galaxies.

3. RESULTS

3.1. Radio-to-Optical Luminosity Ratios

The radio detection rate of the Markarian galaxies brighter than 14.5 mag (40%) is much higher than that of the complete sample of galaxies brighter than 14.5 mag (22%). It is particularly high for Markarian SO galaxies (44%) relative to "normal" SO galaxies (12%). To make a more useful comparison of the physical properties of Markarian galaxies and normal galaxies, I have computed the ratio R of radio luminosity to optical luminosity for the galaxies in both samples. $R \equiv S$ dex $[0.4\ (m - 12.5)]$ where S is the 13 cm flux density in mJy and m is the corrected photographic magnitude (Dressel 1981).

Distributions of R are shown for Markarian galaxies of several Hubble types (Nilson 1973) in Table I. They are displayed beside R distributions derived for 370 SO galaxies, 820 spiral galaxies, and 225 peculiar galaxies in the normal galaxy survey. To facilitate comparison, each normal galaxy distribution has been normalized to have the same total number of galaxies as the corresponding Markarian galaxy distribution, with Sa, Sb, and Sc distributions being normalized separately within the spiral class. (Nilson's S... class has not been included.) Markarian galaxies show a definite shift away from the low R values found in many normal galaxies. The Markarian SO and peculiar galaxies peak at "intermediate" R values (R ~ 20), with medians several times greater than the normal galaxy medians. The Markarian spiral galaxies peak at R ~ 10, which is twice the median R of normal spirals.

Table I. Numbers of Galaxies in the Markarian Sample and Normalized Numbers of Galaxies in the Complete Sample as a Function of the Ratio R of Radio to Optical Luminosity.

R	SO Galaxies		Spiral Galaxies		Peculiar Galaxies	
	Markarian Sample	Complete Sample	Markarian Sample	Complete Sample	Markarian Sample	Complete Sample
<1.5	2	7.5	2	8.8	2	7.8
1.5- 4.5	0	2.8	9	6.2	2	3.7
4.5-13.5	5	2.9	8	8.0	5	7.7
13.5-40.5	9	1.6	7	3.7	16	8.8
40.5-122	0	0.7	1	0.5	6	3.0
>122	0	0.5	0	0.0	1	1.0

3.2 Radio-to-Infrared Luminosity Ratios

The 13 cm flux densities and far infrared fluxes are strongly correlated for the Markarian galaxies. Nearly all of the 28 galaxies with log FIR(W m^{-2}) ≥ -12.7 were above the 15 mJy detection limit of the radio survey. For these 28 galaxies, the mean difference Δ between log S (W m^{-2} Hz^{-1}) and log FIR (W m^{-2}) is -15.07 ± 0.03, and the dispersion in Δ is 0.18. The correlation persists at lower flux levels, where the radio flux densities have relatively large but random errors (σ = 3.6 mJy). For the 33 galaxies with $-13.2 \leq$ log FIR (W m^{-2}) < -12.7 and with S generally less than 15 mJy, the mean Δ is $-15.15 \pm .06$ and the dispersion is 0.35. These values of Δ are not significantly different from the mean Δ of the Sc galaxies in the magnitude-limited complete sample, which is just the Δ of "normal" disk emission.

There are enough radio detections of Markarian galaxies in this sample to permit separate examinations of SO, spiral, and peculiar galaxies. Peculiar galaxies are defined here as those described by Nilson (1973) as "... peculiar," "... compact," or merely "...". They are usually only 0.5 to 1.0 arcmin in diameter, while other galaxies brighter than 14.5 mag are usually 1.0 to 2.5 arcmin in diameter. Values of Δ are shown in Table II for the SO, spiral, and peculiar galaxies detected at Arecibo and by IRAS. (Galaxies with obviously confused or low quality IRAS fluxes have been excluded. Only 2 galaxies were detected at Arecibo but not by IRAS.) The median Δ for the SO and spiral galaxies in Table II (excluding the anomalous value for Mar 321) is -15.10 ± 0.03, and the dispersion is 0.10. The median Δ for the peculiar galaxies is -14.88 ± 0.02, and the dispersion is 0.07. The peculiar galaxies thus emit roughly 60% more radio emission per unit infrared emission than the SO and spiral galaxies do.

Table II. Values of Δ = log S($Wm^{-2}Hz^{-1}$) - log FIR(Wm^{-2}) for SO, Spiral, and Peculiar Galaxies Detected at Arecibo and by IRAS.

SO Galaxies		Spiral Galaxies		Peculiar Galaxies	
Markarian Number	Δ	Markarian Number	Δ	Markarian Number	Δ
531	-15.21	319	-15.04	325	-14.93
534	-15.04	321	-14.43	363	-14.92
1002	-15.20	323	-15.03	418	-14.80
1088	-15.04	326	-15.12	432	-15.02
1194	-15.14	404	-15.02	479	-14.81
		545	-15.03	518	-14.92
		1183	-15.01	1027	-14.86
		1466	-15.34	1233	-14.88
				1304	-14.80

4. DISCUSSION

Markarian galaxies typically emit several times as much radio luminosity per unit optical luminosity as "normal" galaxies of the same Hubble type. This implies that most of the radio emission in Markarian galaxies is related to the "star-burst" population that produces their characteristically powerful ultraviolet emission. Since most of the ultraviolet emission is absorbed by dust and converted to infrared emission, the ratio of radio flux to infrared flux in these galaxies is a measure of the radio luminosity produced per unit of "star-burst" stellar luminosity. Remarkably, this ratio is similar to that produced by the disks of "normal" Sc galaxies. Star-forming regions thus appear to produce similar amounts of synchrotron power per unit stellar ultraviolet thermal power (roughly, synchrotron power per star recently formed) in a very wide range of physical conditions. This study confirms the conclusions of Helou et al. (1985), who compared a much smaller sample of "star-burst" galaxies to "normal" spiral galaxies.

The significant excess of radio emission per unit infrared emission of the peculiar galaxies, relative to the SO and spiral galaxies, remains to be explained. It is not due to any power-dependent selection effect: the galaxies of each type span the same range in far infrared power. Nor is it due to resolution of the radio sources in the somewhat larger SO and spiral galaxies: flux errors due to resolution should be less than 10% in most cases (Dressel and Condon 1978). The infrared fluxes are generally well above the level where systematic errors are known to exist in the IRAS point source catalog. The temperature-sensitive ratio of the fluxes at 60 and 100 microns covers the same range for the peculiar galaxies and the SO and spiral galaxies. Since many of the peculiar galaxies are "disturbed" in appearance (Nilson 1973), it is possible that tidal interactions are involved in generating "extra" radio sources of non-stellar origin. Alternatively, these compact galaxies may have stronger magnetic fields, or may produce a higher proportion of supernova progenitors in their burst populations.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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